Resonant scattering studies of nanometer-scale structure-property relationships (mostly magnetism)

J. B. Kortright
Materials Sciences Division
Lawrence Berkeley National Lab
Berkeley, California 94720
JBKortright@lbl.gov

X-ray scattering measurements in reciprocal space to resolve structure in real space are one of the most important uses of x-rays in fundamental and applied research. Such scattering using soft x-rays has been slow to gain popularity for a variety of reasons, including their long wavelengths (poorer spatial resolution) and relatively strong absorption. However, the combination of very sharp core resonances for important elements spread across the periodic table, and the growing interest in structural organization at length scales ranging from 1 nanometer to 1 micron is causing researchers to consider the value of resonant soft x-ray scattering as a valuable tool. What were once small-angle scattering measurements can now be made with greater ease at larger angles. Surprisingly strong resonances in charge and magnetic scattering factors can literally raise signals up from below noise levels by providing scattering contrast mechanisms not available in hard x-ray or neutron scattering measurements. Sensitivity to very small sample volumes results from these strong resonant cross-sections. Coherent scattering techniques complement more traditional incoherent scattering measurements.

At LBNL's Advanced Light Source we have been developing and applying resonant scattering techniques primarily to magnetic systems, where magnetic as well as chemical structure are both of interest. One class of systems that has been extensively studied is based on Co/Pt multilayer films having perpendicular anisotropy, that easily from stripe domains providing extremely strong magnetic scattering centers [1]. When domains are present, they produce strong magnetic peaks that are purely magnetic in origin (Fig. 1). When the magnetization is saturated, a weaker peak at much higher q remains that is due to chemical heterogeneity associated with the polycrystalline grain structure of these films. When using linear incident polarization this scattering reflects the magnetic-magnetic and charge-charge correlations, but not their cross-correlation. Coherent magnetic scattering studies have found that the microscopic domain memory is sensitive to the strength of this chemical peak and hence to the degree of chemical heterogeneity in these films [2]. Resonant scattering has also been used to study domain structure through reversal in hybrid films based on the Co/Pt system, including exchange bias [3] and indirect antiferromagnetic exchange coupling [4]. Details of domain structure and wall motion during reversal have been studied by following the behavior of higher magnetic scattering harmonics of aligned stripe domains [5].

Resonant scattering has provided the first direct measurement the magnetic correlation length in granular alloy films that constitute longitudinal (in-plane) magnetic recording media [6]. This is demonstrated in Figure 2 that shows scattering data for three different alloy films that represent a historical progression of recording media. Co is the predominant magnetic constituent of these alloys, and so scattering data at the Co L_3 edge contains both magnetic and charge information. Cr is a nominally nonmagnetic constituent, and data collected at the Cr L_3 edge contains primarily charge-charge correlations. Scaling these data at high q and subtracting, then, leaves a spectrum re-

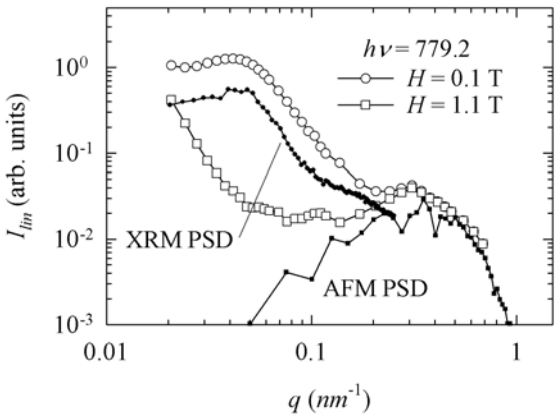

Figure 1

flecting largely magnetic correlations. For the CoCr and CoPtCr alloys, the magnetic (Co – Cr) peak indicates that magnetic correlations are 4-5 times longer than the chemical grain size, while addition of B shifts the magnetic peak to higher q and thus significantly reduces the magnetic correlation length, in agreement with improved recording density. We have found that modeling the energy spectra at the chemical grain peak provides a meaningful estimate of the chemical composition difference between the magnetic grain centers and non-magnetic grain boundaries in these systems [7]. These resonant scattering techniques will be valuable in correlating chemical structure, magnetic structure, and recording performance in future generations of recording media such as perpendicular alloy films [8], and in assessing the potential of more exotic recording materials such as magnetic nanoparticle assemblies.

In addition to resolving lateral magnetic and chemical structure in thin film systems, soft x-rays can depth-resolve such structure via angle- and energy-resolved measurements, including standing wave studies [9].

We have also been investigating the potential of resonant scattering at the carbon K edge (285 eV). This appears to provide an effective means to enhance scattering contrast in polymers and organic systems, where other techniques such as hard x-ray scattering and soft x-ray microscopy may not have sufficient resolution or contrast for structural studies.

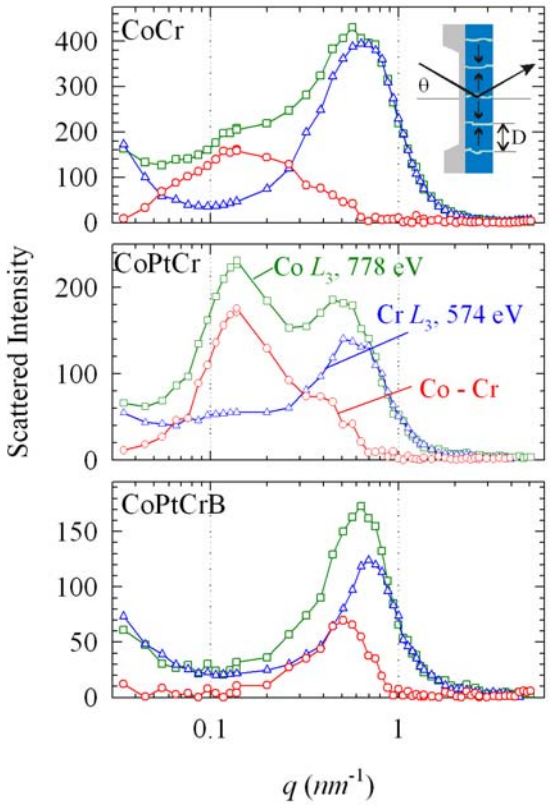

Figure 2

It is clear that many opportunities exist to use resonant scattering in the soft x-ray range to study a variety of scientifically interesting and technologically relevant heterogeneous structures. At high-energy synchrotrons such as the APS it makes most sense to develop capabilities for applications in the 500 – 3000 eV region.

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